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# ***Vehicle Gap Analysis Program***

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US Army Engineer Research & Development Center

**Military Operations Research Society  
75th Symposium  
*June 12 – 14, 2007***

**Presented By:**

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# ***Presentation Outline***

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- Introduction to ERDC mobility research
- Statement of research problem, objective and approach
- Simulation of terrain mechanics
- Terrain representation
- Terrain mechanics verification
- Where we're at now
- VAGP Interface
- Conclusions



# ERDC's Mobility R&D Mission

The ERDC mobility research mission is focused on developing high resolution, component-level mobility representations that produce consistent single- and unit-level vehicle mobility in live, virtual, and constructive M&S environments.

Component-Level Testing



Real-Time Simulations



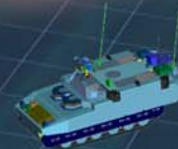
Acquisition Testing



High-Fidelity Modeling



Tactical Mobility Modeling



System-Level Testing



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# Research Problem

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- The Future Combat System Operational Requirements Document requires that manned and unmanned ground vehicles be capable of negotiating gaps 1.5- to 4.0-meters wide
- Current vehicle performance models lack the fidelity and accuracy to predict a vehicle's capability to negotiate deformable gaps



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# Research Objective

- The objective of this research is to develop physics based simulation and analysis capabilities to accurately predict vehicles crossing deformable terrains
- Develop terrain mechanics models for use with on-board robotic vehicles for decision logic
- Develop tactical decision aides for maneuver support





# Research Approach

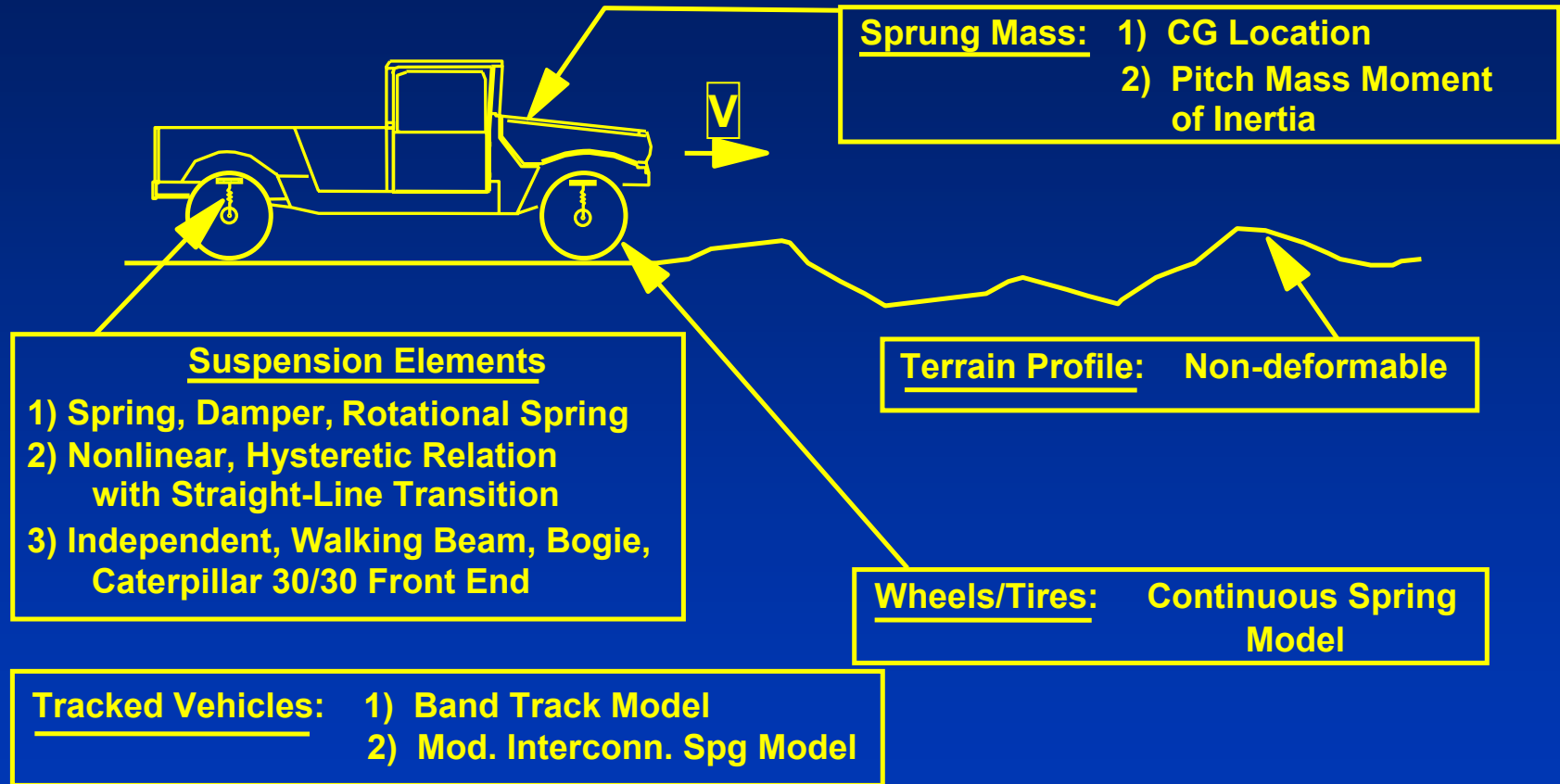
- Use an existing vehicle dynamics software package to demonstrate research and develop new analysis tool
  - The 2-D Vehicle Dynamics (VehDyn II) software package distributed with the NATO Reference Mobility Model (NRMM) was selected as the demonstration platform
- Integrate existing terrain mechanics models
  - Use soils models developed for “whole” traction element representation
  - Use soils models dependent on standard military trafficability kits (hand-held cone penetrometer)
- Develop vehicle chassis and terrain contact interactions
- Develop a vehicle driver model based on the vehicle’s propulsion system





# VehDyn II

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# Terrain Mechanics Model (Wheels)

- The fundamental traction element forces for fine-grained and coarse-grained soils are estimated from specifically derived numerics
- The clay numeric ( $\Pi_c$ ) is a function of the  $RCI$ , traction element nominal contact length and width; tire section width, diameter, and deflection
- The sand numeric ( $\Pi_s$ ) is a function of the  $CI$  and a similar set of measurable traction element items

$$\Pi_c = \frac{RCI(bd)}{w(1 - \delta/h)^{3/2} (1 + b/d)^{3/4}}$$

Fine-grained model

$$\Pi_s = \frac{CI(bd)^{3/2}}{w(1 - \delta/h)^3}$$

Coarse-grained model

Where:  $RCI$ ,  $CI$  = Soil strength  
 $b$  = Tire section width  
 $d$  = Nominal wheel diameter  
 $h$  = Tire section height  
 $\delta$  = Tire deflection  
 $w$  = Weight beneath tire



# Terrain Mechanics Model (Wheels)

- The numeric ( $\Pi$ ) is combined with vehicle performance results to predict drawbar and motion resistance for fine- and course-grained soils
- The equations show the performance parameter as a coefficient based on the weight of the traction element

$$\frac{D}{w} = 0.5 \text{Log}_{10} (i/i_{SP}), \quad i_{SP} = \frac{21}{\Pi_C^{5/2}}$$

Fine-grained

$$\frac{R}{w} = \frac{12}{\Pi_C^2} + .0007$$

$$\frac{D}{w} = 0.52 - \frac{396}{\Pi_{DP} + 557}, \quad \Pi_{DP} = \Pi_S \frac{1}{j^{1/2}}$$

$$\frac{R}{w} = X_j + \sqrt{X_j^2 + .0000457 \Pi_{Rj} + .008}$$

$$X_j = 0.44 - .002287 \Pi_{Rj}$$

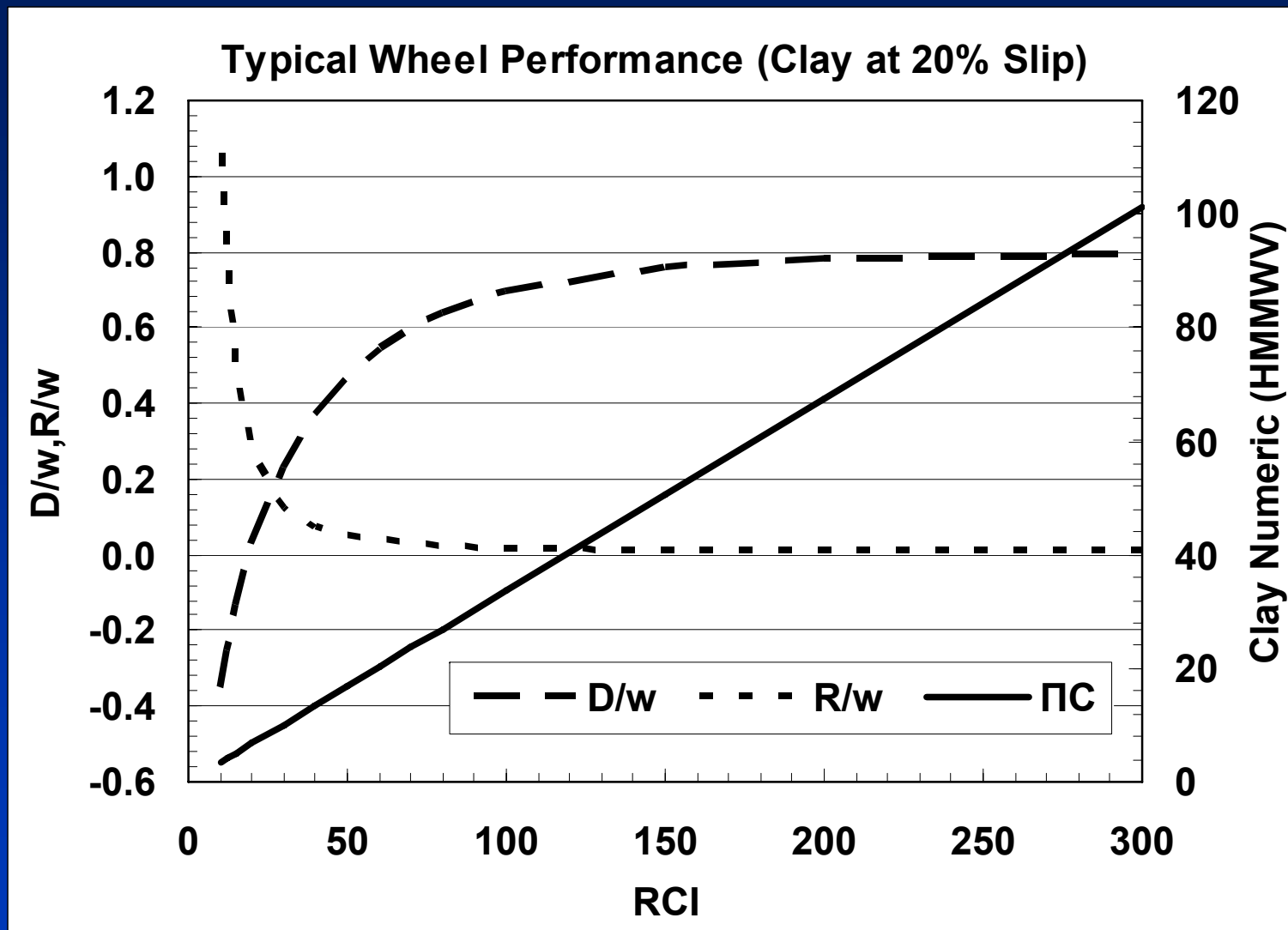
$$\Pi_{Rj} = \Pi_S \bullet \frac{j^{1/2}}{1 + b/d}$$

Course-grained



# Terrain Mechanics Model (Wheels)

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# Terrain Mechanics Model (Wheels)

- A variant of the clay numeric ( $\Pi_{CZ}$ ) and the sand numeric ( $\Pi_{SZ}$ ) is used to estimate wheel sinkage

$$\Pi_{Cz} = \frac{RCI(bd)}{w(1-\delta/h)^{3/2}}$$

Fine-grained  
sinkage

$$\frac{z_p}{d} = \frac{5}{\left( \frac{\Pi_{Cz}}{\text{slip}_{SP}^{1/5}} \right)^{5/3}}$$

$$Z_n = Z_1 \sqrt{n}$$

Sinkage for n vehicle passes

$$Z_1 = \sqrt{Z_{U_1}^2 + Z_{P_1}^2 + Z_{U_2}^2 + \dots + Z_{P_m}^2}$$

Sinkage for m traction elements

$$\Pi_{Sz} = \Pi_s \bullet \frac{1}{1 + b/d}$$

Coarse-grained  
sinkage

$$\frac{z_p}{d} = \frac{14}{\Pi_{SZ}}$$



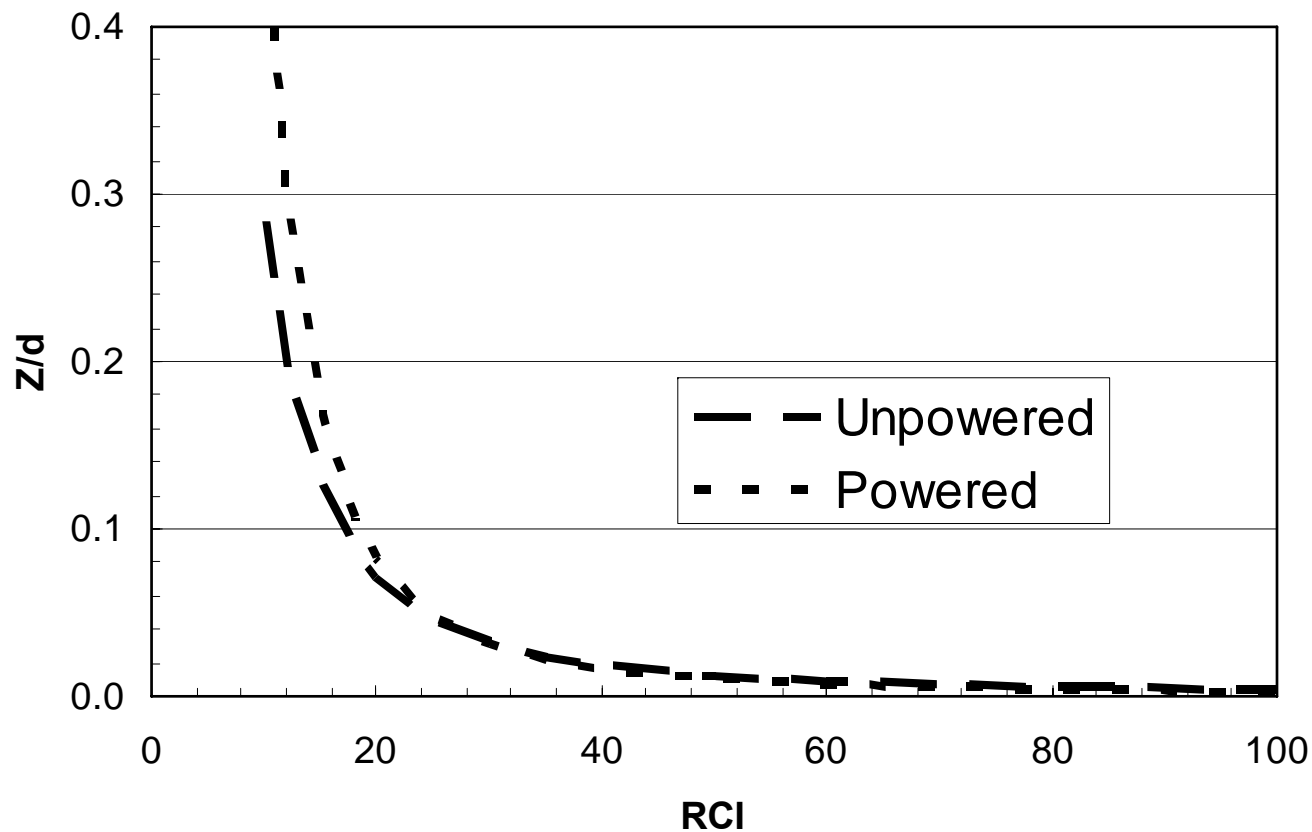


# Terrain Mechanics Model (Wheels)

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## Typical Wheel Sinkage (Clay)

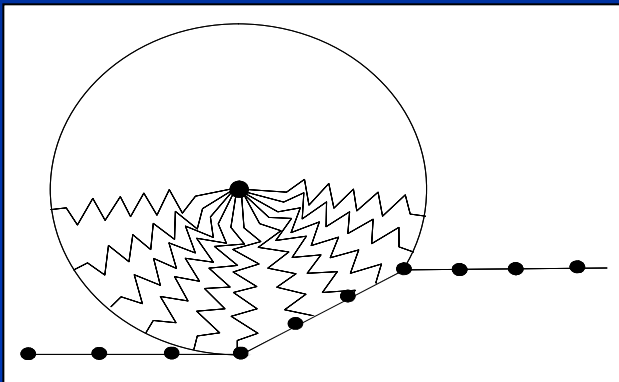


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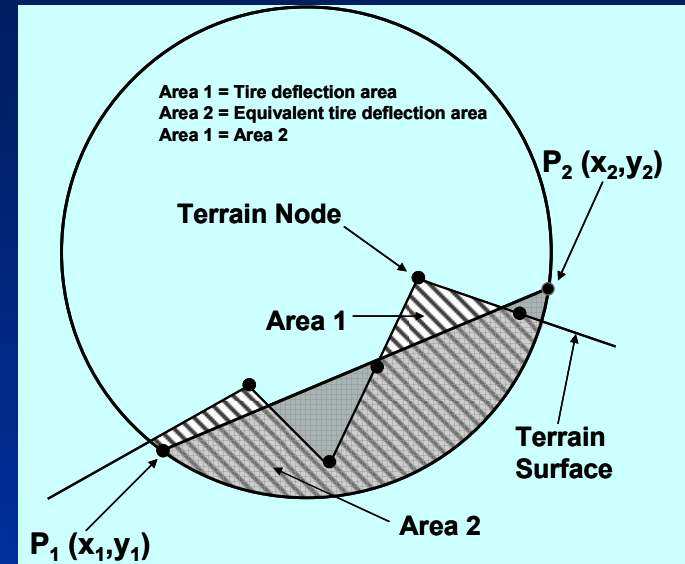


# Terrain Mechanics Model (Wheels)

- The terrain is represented by a series of terrain nodes
- The traction element sinkage is determined and used to calculate the sinkage at the current time step that applies to each terrain node in contact with the traction element



Continuous spring tire model and terrain nodes



$$S_c = (V \times T) / C \times S$$

S = Predicted total sinkage (in) for entire wheel

C = Chord Length (in) from P1 to P2

T = Time step (sec)

V = Vehicle's instantaneous velocity (in/sec)

$S_c$  = Sinkage (in) this time step



# ***Terrain Mechanics Model (Tracks)***

- The fundamental traction element forces for fine-grained and coarse-grained soils are estimated from specifically derived numerics and empirical relationships
- The clay numeric ( $\Pi_c$ ) is a function of the RCI, traction element nominal contact length and track width
- The sand numeric ( $\Pi_s$ ) is a function of the CI and the same set of measurable traction element items

$$\Pi_c = \frac{RCI(bl)}{w}$$

Fine-grained model

$$\Pi_s = \frac{G(bl)^{3/2}}{w}; \quad G = CI * 0.8645 / 3$$

Coarse-grained model

Where:

RCI, CI = Soil strength

G = Soil strength gradient

b = Track width

l = Nominal contact length (ground contact length)

w = Weight beneath track



# ***Terrain Mechanics Model (Tracks)***

- A variant of the clay numeric ( $\Pi_C$ ) and the sand numeric ( $\Pi_S$ ) is used to estimate wheel sinkage

$$\frac{Z}{l} = 0.00443e^{\frac{5.887}{\Pi_C}}$$

Fine-grained sinkage

$$\frac{Z}{l} = 0.030292 + \frac{0.85437}{\Pi_S} - \frac{0.48443}{\Pi_S^2}$$

Coarse-grained sinkage

$$Z_n = Z_1 \sqrt{n}$$

Sinkage for n vehicle passes

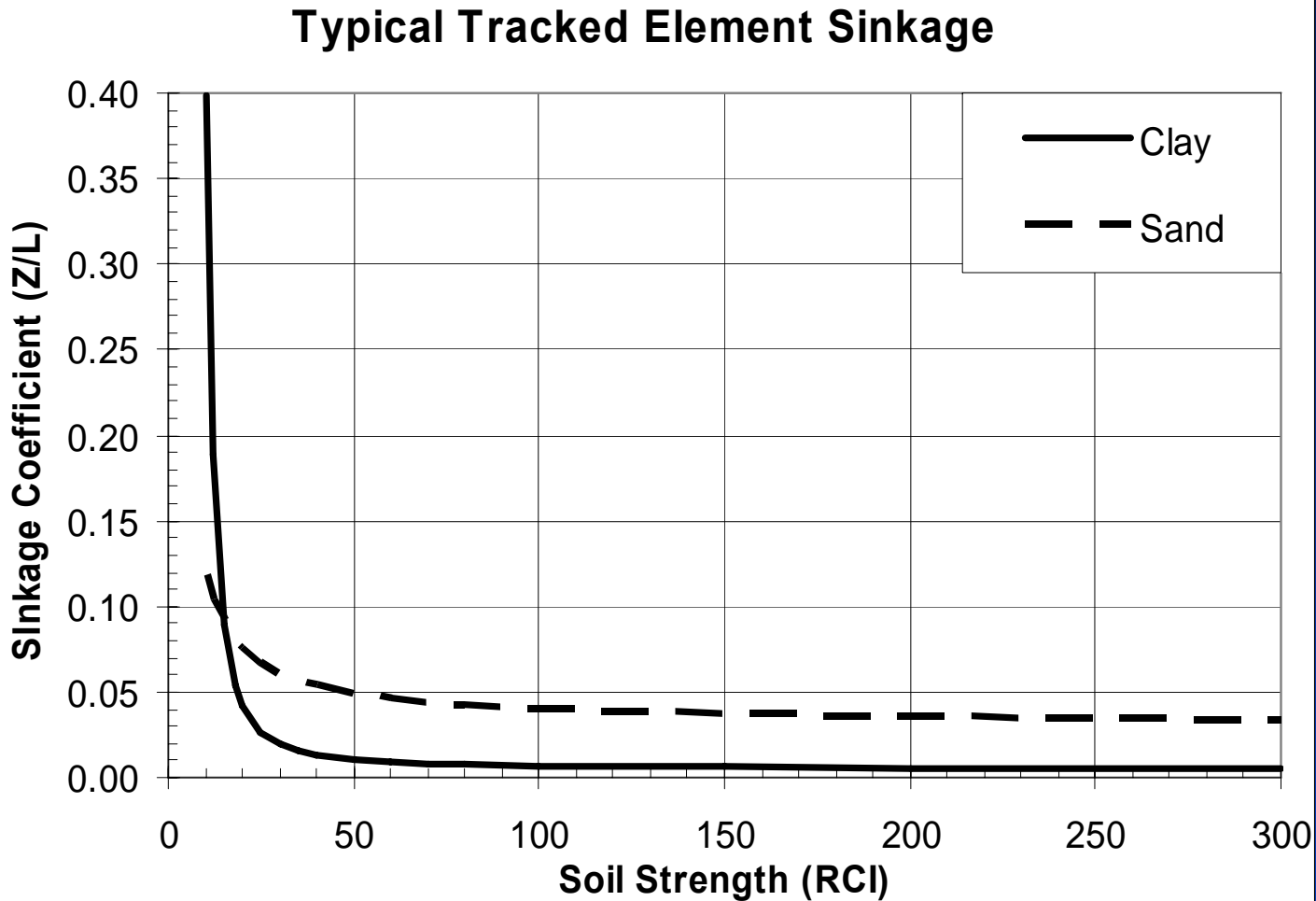
$$Z_1 = \sqrt{Z_{U_1}^2 + Z_{P_1}^2 + Z_{U_2}^2 + \dots + Z_{P_m}^2}$$

Sinkage for m traction elements



# Terrain Mechanics Model (Tracks)

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# Terrain Mechanics Model (Tracks)

- Drawbar pull for fine-grained soils are calculated using tracked vehicle empirical relationships
- The sand numeric ( $\Pi$ ) is combined with vehicle performance results to predict drawbar for course-grained soils
- The equations show the performance parameter as a coefficient based on the weight of the traction element

$$\frac{D}{w} = A + \frac{B}{RCIx + C}$$

	A	B	C
FGa	0.7814494	-6.709946	7.854210
FGb	0.8117813	-5.737010	6.507696
CPF<4	0.8476903	-4.974673	5.724387

FGa = CPF ≥ 4, USCS: ML, CL, MLCL, OL, SM, SMSC, GM  
 FGb = CPF ≥ 4, USCS: SC, GC, CH, MH, OH

Fine-grained

$$\frac{D}{w} = k1 + k2 \log_{10}(\Pi_s)$$

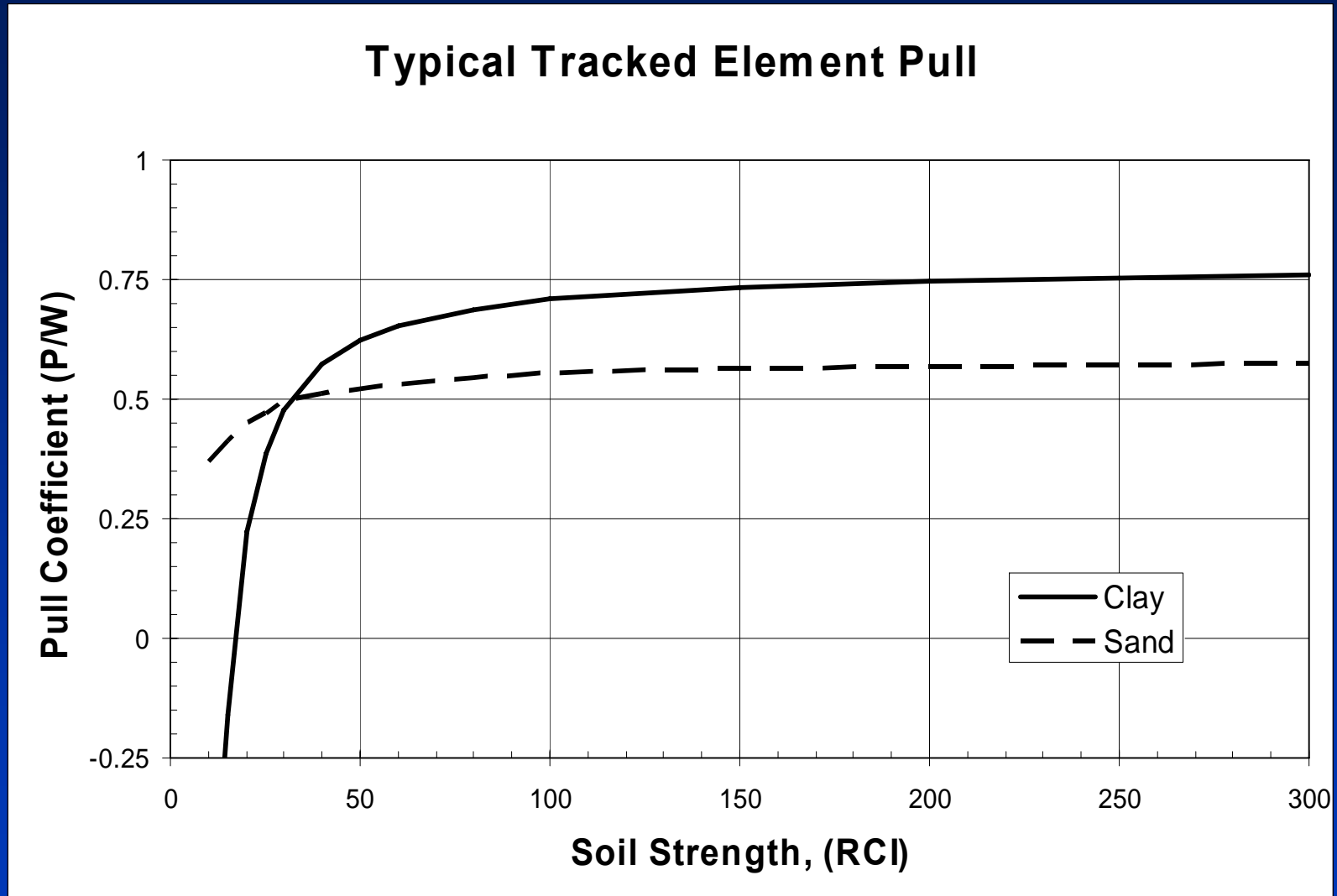
k1	k2	Condition
0	0	$\Pi_s \leq 0$
0.121	0.258	$0 < \Pi_s \leq 25$
0.339	0.109	$25 < \Pi_s \leq 100$
0.481	0.038	$100 < \Pi_s \leq 1000$
0.595	0	$\Pi_s > 1000$
Track Type		Max
Flexible		0.3926
Girderized		0.5365

Course-grained



# Terrain Mechanics Model (Tracks)

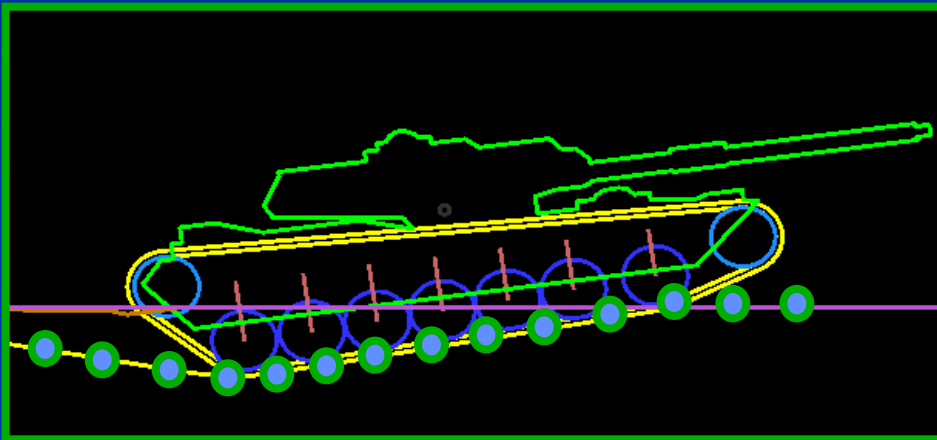
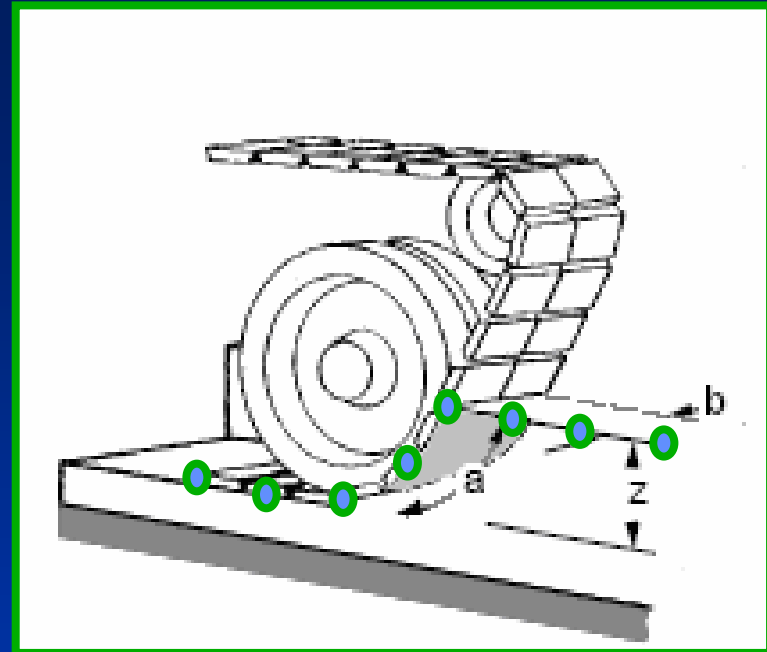
Typical Tracked Element Pull





# ***Terrain Mechanics Model (Tracks)***

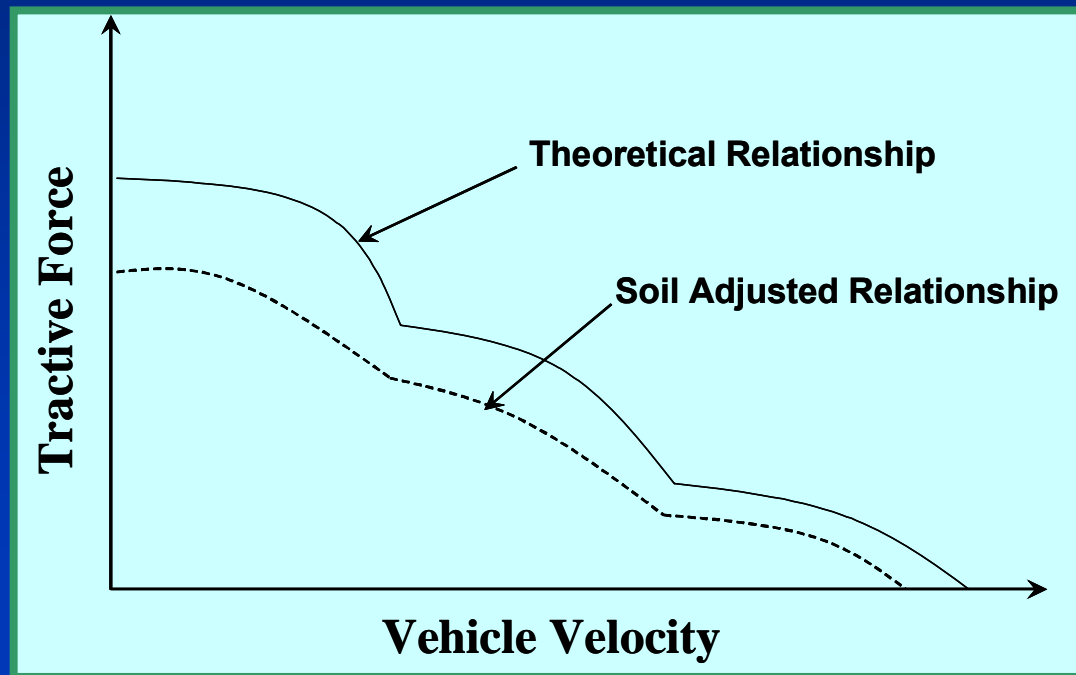
- The terrain is represented by a series of terrain nodes
- The traction element sinkage is determined and used to calculate the sinkage at the current time step that applies to each terrain node in contact with the traction element





# Vehicle Traction

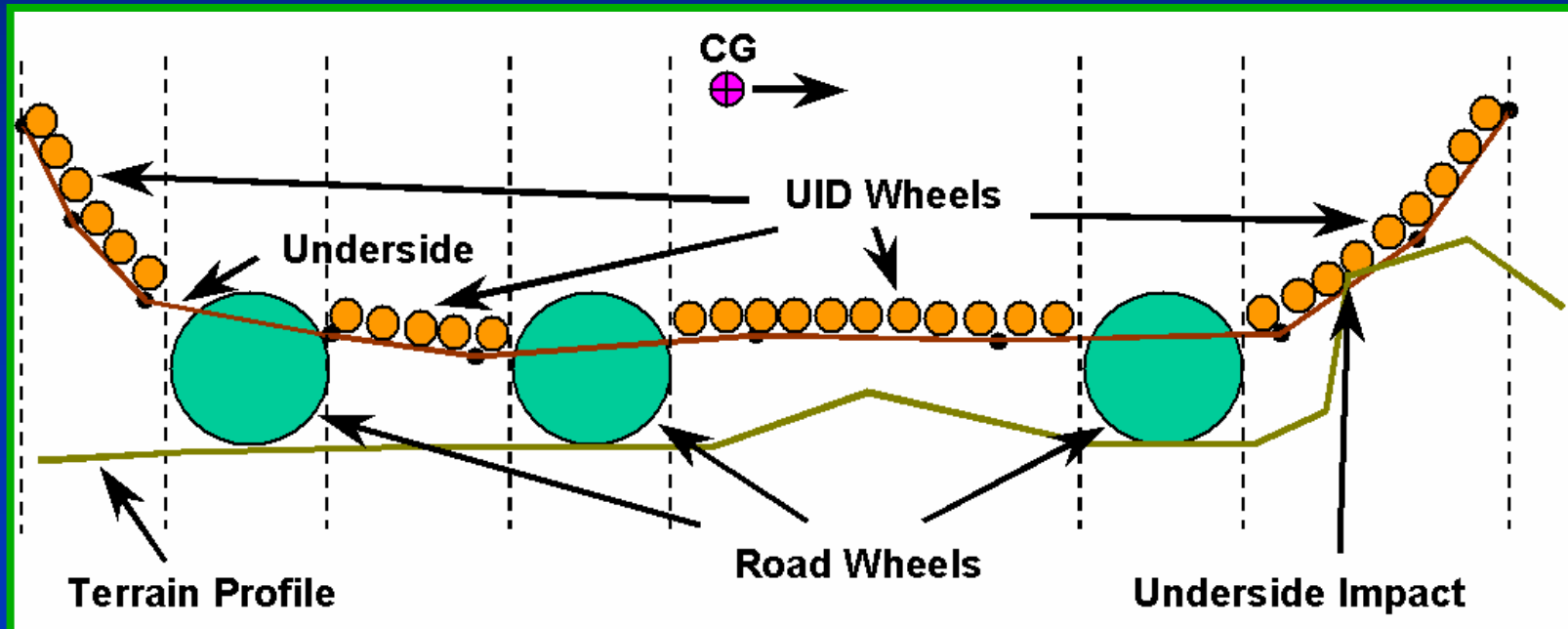
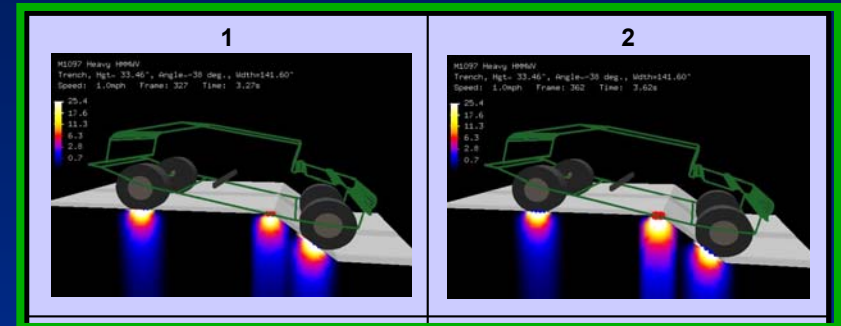
- The vehicle traction is determined by using the theoretical tractive force and speed relationship developed from the vehicle's propulsion system
- It is adjusted based on the soil properties and numeric relationships





# Chassis/Terrain Interaction

- Underside Impact Detection (UID) “drag” wheels placed all along vehicle underside
- Await impact with the ground
- Produce normal and tangential (drag) forces applied to chassis
- Applied laterally across half the vehicle width like long “tubes”







# Gap Crossing Verification

- Vehicle accelerates to 2 mph
- Chassis changes color based on tractive force relationship
- Terrain deformation indicated by different colored lines



M113 / Derived from M113A2 file  
Ft. Chaffee (9-10-86) 8  
Speed: 0.7mph Frame: 1 Time: 0.01s



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# VCI Verification

- Vehicle accelerates to 10 mph
- Chassis changes color based on tractive force relationship
- Terrain deformation indicated by different colored lines





# Hard Surface Slope Verification

- **DB = Drawbar**
  - Drawbar pull relationship is used to calculate the “theoretical” maximum slope

<i>Slope Climbing (Percent)</i>		
<i>Vehicle</i>	<i>VGAP</i>	<i>DB Slope</i>
M1097 (HMMWV)	81.6	75.5
M1078 (LMTV)	81.3	75.5
LAV	75.8	75.4
M923	68.0	73.5
M977 (HEMTT)	63.7	74.9
M113	81.6	104.2
M2A2 (BFV)	73.4	104.3
M1A1	78.5	104.1





# ***Fine Grain VCI1 Verification***

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- Vehicle Cone Index  $x$  (VCI $x$ ) is the minimum soil strength required to support the vehicle for  $x$  number of passes
- Soil strength is measured in terms of Remolded Cone Index (RCI)
- Typical field test variation is +/- 3 RCI points
- NRMM is a validated vehicle model for calculating VCI $x$

Computed Fine Grain VCI1		
	VGAP	NRMMII
M1097 (HMMWV)	20	22.2
M1078 (LMTV)	26	27.1
LAV	32	30.2
M923	17	29.7
M977 (HEMTT)	33	32.1
M113	16	15.2
M2A2 (BFV)	20	18.5
M1A1	26	25.3



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# Coarse Grain VCI1 Verification

- Vehicle Cone Index  $x$  (VCI $x$ ) is the minimum soil strength required to support the vehicle for  $x$  number of passes
- Soil strength is measured in terms of Cone Index (CI)
- Typical field test variation is  $\pm 3$  RCI points
- NRMM is a validated vehicle model for calculating VCI $x$

Computed Coarse Grain (SP) VCI1

	VGAP	NRMMII
M1097 (HMMWV)	47	33.6
M1078 (LMTV)	58	46.1
LAV	70	66.2
M923	47	51.4
M977 (HEMTT)	32	40.5
M113	1	0.4
M2A2 (BFV)	1	0.3
M1A1	1	0.4



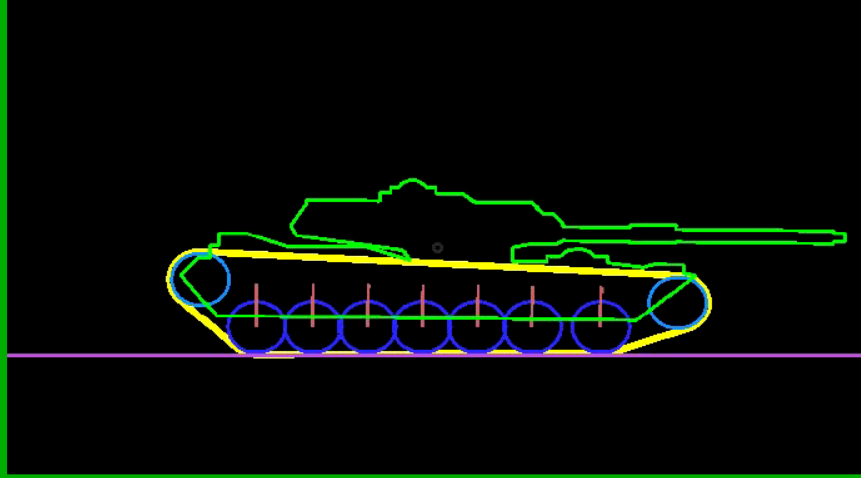




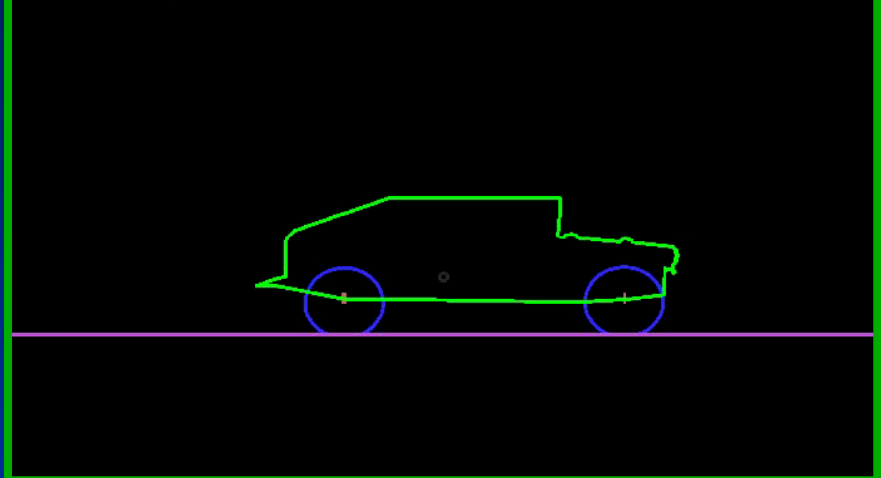
# Where We're At Now

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M1 ABRAMS MAINBATTLE TANK  
Demo Terrain  
Speed: 1.6mph Frame: 1 Time: 0.01s



M1097 Heavy HMMVV  
Demo Terrain  
Speed: 0.6mph Frame: 1 Time: 0.03s



- Tire/Track interaction with deformable soil relationships based on soil type and strength
  - Soil strengths changes along the simulated profile
- Vehicles are driven by soil adjusted tractive-force relationship
- Variable forward acceleration
- Vehicle Underside Impact Detection



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# VGAP Interface

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### Recon Data Gap

File Help

Gaps Already Defined: Ditch Add New Gap

Inputs

Upload Soil File: C:\Vgap\_New\_dflG Browse View Soil Plot

Upload Geometry LADAR: C:\Vgap\_New\_dflG Browse View Geometry

Upload Water Sensor Data:  Browse

Save Advanced Options Generate Gap Data File Perform Gap Analysis

### Initial Gap Input

File Help

Wet Is the Gap wet or dry?

Recon Data Do you have recon data or do you want to perform analysis with a standard gap?

Multiple Vehicles Do you want to analyze a single vehicle crossing or multiple vehicles?

Name of Vehicles	Number of Vehicles	Convoy Order
M242 BFV	5	1
M977 HEMTT	6	1
M1A1	7	1
M113A1 APC	2	1
1 AV	3	1

Add Vehicle Delete Vehicle

Continue

### Introduction

# VGap

## BATTLESPACE GAP

### DEFINITION AND DEFEAT

### Vehicle Gap Analysis Program

View Gap Analysis Results Perform New Gap Analysis

### Soil Strength Wizard

For the typical soldier walking in the soil:

No A footprint greater than 2-inches deep is observed.

No A 2-inch deep footprint is observed.

No A 1-inch deep footprint is observed.

No A well defined footprint is observed.

No A trace footprint is observed.

If the soldier does not leave a footprint he should try to penetrate the ground surface using the thumb:

No The thumb easily penetrates the ground surface.

### Define Standard Gap

Standard Gaps: Standard

A = 4 ft B = 5 ft C = 8 ft D = 5 ft E = 9 ft

Input Gap Properties

SP - Coarse Gra Soil Type Help Value Depth (ft)

32 Soil Strength Help Value Velocity Help

Generate Data File Save Edit Cancel Perform Analysis

### Analysis

Output

Mission Status:

Status	Name of Vehicle	Limiting Condition
<span>Green Dot</span>	M242 BFV	Vehicle completed profile
<span>Red Dot</span>	M242 BFV	Insufficient traction to overcome soil/slope resistance

View Animation Save Results Assess Defeat Options

Geometry Profile: 3D

Geometry Profile: 2D

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# Conclusions

- A set of equations and methodologies have been presented that were used to create a new vehicle mobility analysis tool
- This terrain mechanics modeling approach is based on algorithms for whole wheel tests (soil bin) and full vehicle field tests
- This approach is expected to yield representative performance (longitudinal traction, resistance and sinkage) for vehicles in a dynamic simulated environment
- The terrain mechanics model is applicable to a variety of simulation environments and on-board robotic decision logic